

Results from Carbon Dioxide Washout Testing Using a Suited Manikin Test Apparatus with a Space Suit Ventilation Test Loop

Cinda Chullen¹

NASA Johnson Space Center, Houston, Texas, 77058

Bruce Conger,² Summer McMillin,³ Walt Vonau,⁴ Bryan Kanne,⁵ Adam Korona,⁶
Jacobs, Houston, Texas, 77058

and

Mike Swickrath⁷

Battelle Memorial Institute, Columbus, Ohio, 43201

NASA is developing an advanced portable life support system (PLSS) to meet the needs of a new NASA advanced space suit. The PLSS is one of the most critical aspects of the space suit providing the necessary oxygen, ventilation, and thermal protection for an astronaut performing a spacewalk. The ventilation subsystem in the PLSS must provide sufficient carbon dioxide (CO₂) removal and ensure that the CO₂ is washed away from the oronasal region of the astronaut. CO₂ washout is a term used to describe the mechanism by which CO₂ levels are controlled within the helmet to limit the concentration of CO₂ inhaled by the astronaut. Accumulation of CO₂ in the helmet or throughout the ventilation loop could cause the suited astronaut to experience hypercapnia (excessive carbon dioxide in the blood). A suited manikin test apparatus (SMTA) integrated with a space suit ventilation test loop was designed, developed, and assembled at NASA in order to experimentally validate adequate CO₂ removal throughout the PLSS ventilation subsystem and to quantify CO₂ washout performance under various conditions. The test results from this integrated system will be used to validate analytical models and augment human testing. This paper presents the system integration of the PLSS ventilation test loop with the SMTA including the newly developed regenerative Rapid Cycle Amine component used for CO₂ removal and tidal breathing capability to emulate the human. The testing and analytical results of the integrated system are presented along with future work.

Nomenclature

<i>acfm</i>	=	actual cubic feet per minute
<i>AEMU</i>	=	Advanced Extravehicular Mobility Unit
<i>APLSS</i>	=	Advanced Space Suit Portable Life Support Subsystem

¹ Project Engineer, Space Suit and Crew Survival Systems Branch, Crew and Thermal Systems Division, 2101 NASA Parkway/EC5.

² Engineering Analysis Lead, Thermal and Environmental Analysis, 2224 Bay Area Blvd./JE-5EA.

³ Project Engineer, Hardware Systems Project Engineering, 2224 Bay Area Blvd./JE-6WC.

⁴ Engineering Analyst, Thermal and Environmental Analysis, 2224 Bay Area Blvd./JE-5EA.

⁵ Laboratory Technician, Space Environment Simulation, 2224 Bay Area Blvd.

⁶ Systems Engineer, Systems Engineering Services, 2224 Bay Area Blvd./JE-6WC

⁷ Principal Research Scientist, Energy Systems, 505 King Ave.

<i>BTU</i>	=	British thermal units
<i>CEM</i>	=	controlled evaporation mixer
<i>CFD</i>	=	computational fluid dynamics
<i>CO₂</i>	=	carbon dioxide
<i>COTS</i>	=	commercial off-the-shelf
<i>EMU</i>	=	Extravehicular Mobility Unit
<i>EVA</i>	=	extravehicular activity
<i>H₂O</i>	=	water vapor
<i>hr</i>	=	hour
<i>ISS</i>	=	International Space Station
<i>IVTS</i>	=	Integrated Ventilation Test System
<i>JSC</i>	=	Johnson Space Center
<i>min</i>	=	minute
<i>mmHg</i>	=	millimeters of mercury
<i>O₂</i>	=	oxygen
<i>N₂</i>	=	nitrogen
<i>PLSS</i>	=	portable life support subsystem
<i>ppCO₂</i>	=	partial pressure of carbon dioxide
<i>psia</i>	=	pounds per square inch absolute
<i>PUMA</i>	=	Portable Unit for Metabolic Analysis
<i>REI</i>	=	Rear Entry I-Suit
<i>RCA</i>	=	Rapid Cycle Amine
<i>SMTA</i>	=	suited manikin test apparatus
<i>TCC</i>	=	Trace Contaminant Control

I. Introduction

A space suit provides a safe haven for an astronaut performing a microgravity extravehicular activity (EVA) in the vacuum of space. This safe haven is a culmination of tremendous technical challenges in the operation of the suit. It is critical that these challenges be continually solved in both the current Extravehicular Mobility Unit (EMU) used on the International Space Station (ISS) and in the new Advanced EMU (AEMU) for future human space exploration missions which is currently under development at NASA Johnson Space Center. Although, the ISS no longer uses the EMU for buildup, the EMU is used for critical operations for sustainability, repairs, and maintenance of the ISS. Future missions will necessitate a space suit not only for sustainability for a vehicle, but for reliability and maintainability of itself as well. The AEMU will need to be regenerable, robust, right-sized, low-powered, and meet the extensive thermal and environmental requirements of the astronaut. It will also need to contain durable hardware for maintaining and monitoring critical life support constituents in the suit. Of all of these technical challenges, the thermal and environmental ones remain the most complex. These set of complex challenges are overcome by using a efficient portable life support system (PLSS) internally to the suit. The EMU uses a PLSS and the AEMU will contain an advanced PLSS.

The AEMU will contain an APLSS to meet the thermal and environmental challenges facing the suit for future missions. The new APLSS will attach to a space suit pressure garment and will have the ability to provide approximately an 8-hour supply of oxygen (O₂) for breathing, suit pressurization, ventilation, humidity control, trace contaminant control, carbon dioxide (CO₂) removal, and thermal control for crew member metabolic heat rejection. One of the most difficult technical environmental challenges facing the PLSS is to ensure the removal of the potentially hazardous CO₂ expired from the astronaut. A regenerative technology known as Rapid Cycle Amine (RCA) is being used for CO₂ removal in the APLSS ventilation system.^{1,2,3,4}

Due to the regenerable nature of the RCA in the APLSS, more of the CO₂ can cycle back through the ventilation loop into the helmet than occurred within the EMU. Exhaled CO₂ could accumulate and be re-inhaled potentially causing hypercapnia or CO₂ toxicity. The symptoms of hypercapnia could be serious such as headache, visual disturbance, impaired mental function, lethargy, dizziness, shortness of breath, and increased heart rate. Unconsciousness, convulsions, and death could be the result of higher CO₂ concentrations.⁵ Minimizing re-inhaled metabolically produced CO₂ within the space suit is paramount. The CO₂ has to be adequately dispersed or “washed out” from the astronaut’s oronasal region within the helmet, adequately removed by the RCA within the ventilation loop and sufficiently monitored throughout the space suit. Combining all these requirement in a space suit makes it critical that the APLSS be more effective and efficient to mitigate this effect. The integration of a multipitude of

variables including helmet and ventilation duct configurations as well as ventilation flow rate are used to control CO₂ washout. As shown in Figure 1, the CO₂ removal components and CO₂ washout are key aspects of the EMU and AEMU for maintaining proper CO₂ levels.

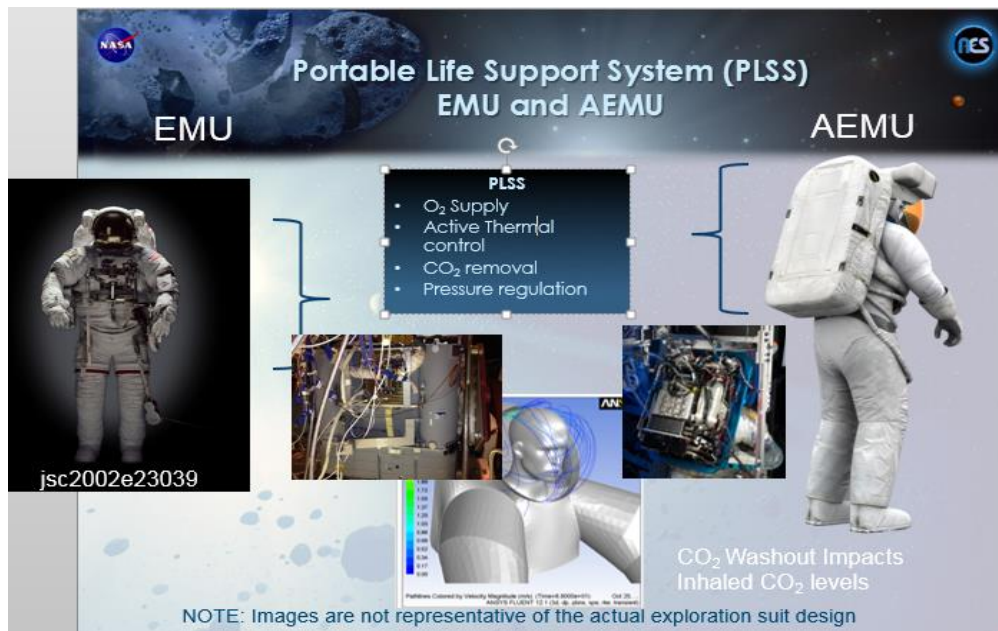


Figure 1. CO₂ Removal components & CO₂ Washout are key aspects of the EMU and AEMU for maintaining proper CO₂ levels (Figure will be updated in final paper)

Over the last several years, NASA has evaluated CO₂ washout in several human test series as explained in Section II, Previous Carbon Dioxide Washout Efforts. The main purpose of these tests have been to analyze the effects of CO₂ washout with different space suit configurations as well as to ensure the crew member receives breathing gas that is safe. These human test trials are vital to evaluate and certify new space suit configurations such as the Z-1 and Z-2 advanced space suits. Because these test trials involve human test subjects, they can be expensive, time consuming, and involve extensive safety protocols. Therefore, research is currently under way at NASA Johnson Space Center (JSC) in the PLSS Laboratory to focus on the CO₂ washout optimization studies using a suited manikin test apparatus (SMTA) integrated with a space suit ventilation test loop. This integrated test system was designed, developed, and assembled at NASA in order to experimentally validate adequate CO₂ removal throughout the PLSS ventilation subsystem and to quantify CO₂ washout performance under various metabolic conditions.

This paper discusses the previous CO₂ washout efforts and describes the system integration of the PLSS ventilation test loop with the SMTA including the RCA for CO₂ removal and tidal breathing capability to emulate the human. The CO₂ washout test plans, testing, and analytical results of the integrated system are presented along with a discussion of future work.

II. Previous Carbon Dioxide Washout Efforts

In the past 5 years, NASA Johnson Space Center has performed several manned pressurized sure tests to: 1) validate that various development suits are safe for 1g evaluations at various metabolic and air flow rates, 2) identify suit inlet flow configurations that create the highest oronasal CO₂ washout, and 3) refine existing CFD models to aid in development of future suit inlet vent designs. These efforts have produced a new standard for measuring oronasal CO₂ levels in a pressurized suit and have continually refined related CFD modeling.

A. 2011 REI Suit Testing

In June 2011, a series of CO₂ washout tests were performed using the Rear Entry I-Suit (REI).⁶ These tests were performed at a suit pressure of 4.3psid and various metabolic rates (resting to 3000 BTU/hr) and various suit airflow rates (4 to 6 acfm). The focus of this test series of tests was to: 1) create standard CO₂ washout testing protocol, 2) refine current CFD models, and 3) correlate CFD modeling to test data. In this series, a treadmill and arm ergometer were identified as the standard pieces of equipment test subjects would use to achieve various metabolic rates for this and future CO₂ washout tests. Several methods were evaluated for sampling oronasal CO₂ levels inside the suit and it was determined that of the methods evaluated, a Hans Rudolph 7450 series Oronasal Mask captured the highest fidelity oronasal CO₂ samples. This mask would be used as the standard for capturing oronasal samples for CO₂ washout testing from 2011 to 2016.



Figure 2: Mask/sensor configuration



Figure 3: Test subject in REI suit using ergometer

B. 2012 Z-1 Suit Testing

The JSC Advanced Pressure Garment Suit Team procured and received a new development suit (Z-1) in January 2012.⁷ The first manned use of this suit was to demonstrate adequate oronasal CO₂ washout for ground testing. This test used the same basic configuration as the 2011 REI CO₂ washout test, and was used to: 1) confirm/validate the protocol used with the REI Suit, 2) validate the Z-1 suit was safe for 1g usage at various metabolic rates, 3) refine CFD models, 3) correlate CFD model to test data at 4.3 psid, and to help define requirements for another development suit that was being planned (Z-2) at that time. The Z-1 suit was shown to have adequate CO₂ washout for 1g laboratory use, and the CO₂ washout protocol used in this and the 2011 REI test appeared to provide consistent results.

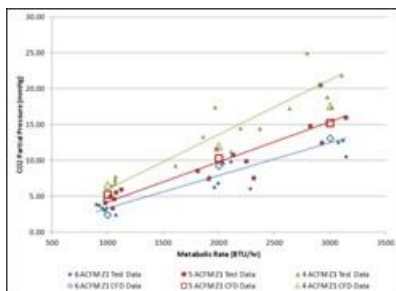


Figure 4: Z-1 Suit CFD vs. CFD compression



Figure 5: Test subject in Z-1 suit on treadmill

C. 2014 Mark-III Vent Configuration Test



Figure 6: Mark-III Suit

Several factors affect oronasal CO₂ levels in a pressurized suit, and in 2014 a test series was conducted to help better understand how different suit inlet configurations affected oronasal CO₂ levels.⁸ A special suit inlet duct was designed and fabricated to allow 6 different airflow configurations to be tested in the Mark-III development space suit. The goals of this test were to: 1) evaluate oronasal CO₂ washout associated with 6 different helmet inlet vent configurations at various metabolic and air flow rate, 2) capture additional data to refine CFD models, and 3) make minor updates to testing protocol to drive out existing error sources. Although there were some differences within each configuration, four

of the six configurations appeared to provide statistically similar results. The remaining two configurations providing more airflow from the sides of the helmet while minimizing airflow over the top of the head. These two configurations appeared to provide somewhat less washout when compared to the other four configurations. The results from this test series were consistent with the two previous studies in that suit airflow rates and metabolic rates were found to have the largest effect on oronasal CO₂ levels.

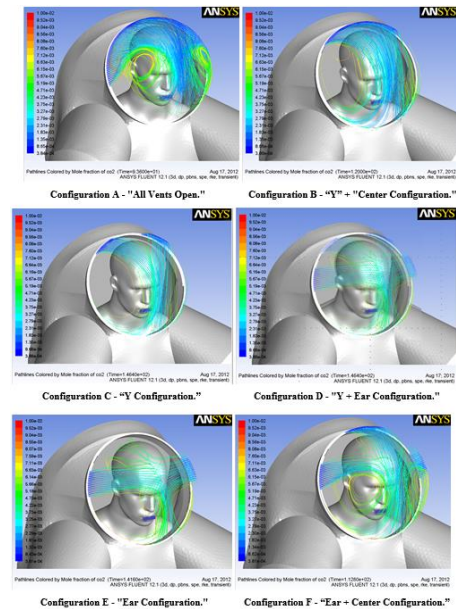


Figure 7: Various inlet configurations to be tested

D. 2015 Mark-III Mask testing



Figure 8: Test Subject wearing the nasal cannula

Although the oronasal mask used in CO₂ washout testing from 2011 to 2015 appeared to capture the desired data, an effort was made to create a lower profile method for collecting oronasal CO₂ levels. The size and shape of the current mask didn't appear to be a major problem for suits with larger volume helmets like the REI, Z-1 and Mark-III, but appeared to significantly alter the inlet airflow path in suits with smaller volume helmets. As a result, several low profile concepts for collecting oronasal CO₂ levels were designed and evaluated in 2014-2015. The most promising design used a COTS nasal cannula. The 2015 Mark-III Mask test series involved several subjects, flow rates and metabolic rates to compare oronasal CO₂ levels measured using the traditional oronasal mask and the COTS nasal cannula. The result of this test series showed that the much lower profile nasal cannula obtained more realistic (less conservative) data and provided smaller variation in day-to-day and subject-to-subject data.⁹ As a result, the nasal cannula has been selected as the new standard for measuring oronasal CO₂ levels in pressurized suits. Future CO₂ washout test using the Z-2 development Space Suit, and eventually in the current Space Station EMU plan to use this sampling method. With this refined sampling configuration and tested data collection system, the next step will be to use this test protocol to refine oronasal CO₂ limit requirements that will be used to design future space suits and related life support systems.

III. SMTA Carbon Dioxide Washout Test Plans

A CO₂ washout test series is currently planned to be performed at JSC to help evaluate the CO₂ concentration levels within a simulated space suit with breathing effects while interfaced to the ventilation loop representing the configuration of the Advanced PLSS.

The objectives of CO₂ washout test series are as follows:

- 1) Use the SMTA breathing manikin to simulate breathing profiles with CO₂ and H₂O, metabolic gas

- consumption, and variation with metabolic rate
- 2) Assess the uniformity of mixing within the SMTA
- 3) Validate CFD model predictions and compare results to human CO₂ washout test results
- 4) Evaluate various helmet ventilation configurations

Test points for SMTA CO₂ washout testing will cycle through the metabolic rates listed in Table 1 for each of the ventilation configurations shown in Figures 6 based on previous CFD analyses.¹⁰ The metabolic rates of 1000 BTU/hr, 2000 BTU/hr and 3000 BTU/hr are the highest priority metabolic rates since these are the values that have been tested in previous human CO₂ washout testing.^{6,7,8,9} The other metabolic rates listed in Table 1 are included in the Priority 5 group of test points. Currently, 315 test points are planned, and they have been grouped into the following priorities:

- Priority 1: Assorted Test Points for RCA Model Development
- Priority 2: Evaluation of duct configurations at 4, 5, and 6 acfm at 15.6 pounds per square inch absolute (psia) and 4 and 6 acfm at 4.3 psia
- Priority 3: Add mask to evaluate differences between human testing and CFD results
- Priority 4: Turned head position evaluation
- Priority 5: Alternate exit port evaluation
- Priority 6: Additional metabolic rate performance evaluation
- Priority 7: Alternate breathing pattern evaluation
- Priority 8: Evaluation of performance at 8.2 psia
- Priority 9: Redo Priority 2 with Closed Loop RCA

Table 1. CO₂ Washout Test Series Metabolic Rates

Simulated Metabolic Rate	CO ₂ Production Rate	H ₂ O Production Rate
BTU/hr	slm	g/min
500	0.387	0.88
800	0.619	1.22
1000	0.774	1.38
1200	0.929	1.47
1600	1.238	1.48
2000	1.548	1.25
3000	2.322	1.25

Test results from priorities 1 through 3 will be analyzed to determine the three best-performing helmet inlet duct configurations. Test points for priorities 3 through 8 will only evaluate these three best-performing inlet duct configurations to reduce the total number of required test points. Priority 9 test points will redo priority 2 test points with a closed loop RCA setup and will assess all helmet ventilation configurations.

IV. Ventilation Laboratory Hardware Descriptions

The Ventilation Test Loop and the SMTA are located in the JSC PLSS Laboratory (JSC Building 7, room 2006). A picture of the two systems are shown in Figure 9 with the vacuum chamber is on the left, the Ventilation Test Loop in the middle and the SMTA on the right. Both the Ventilation Test Loop and the SMTA systems were completed after several years of schematic development, component specification, test rig buildup, and system integration with the primary purpose of conducting RCA performance testing and CO₂ washout testing. The Ventilation Test Loop was primarily designed to replicate the ventilation loop in the APLSS. The main function of the ventilation loop is to remove the CO₂ in the space suit and provide the transport of the breathing gas to the astronaut. The SMTA was designed to emulate the human in the loop with breathing capability. With both the Ventilation Test Loop and the SMTA integrated together, the test rig functions as the APLSS ventilation loop combined with the simulated astronaut in the loop.

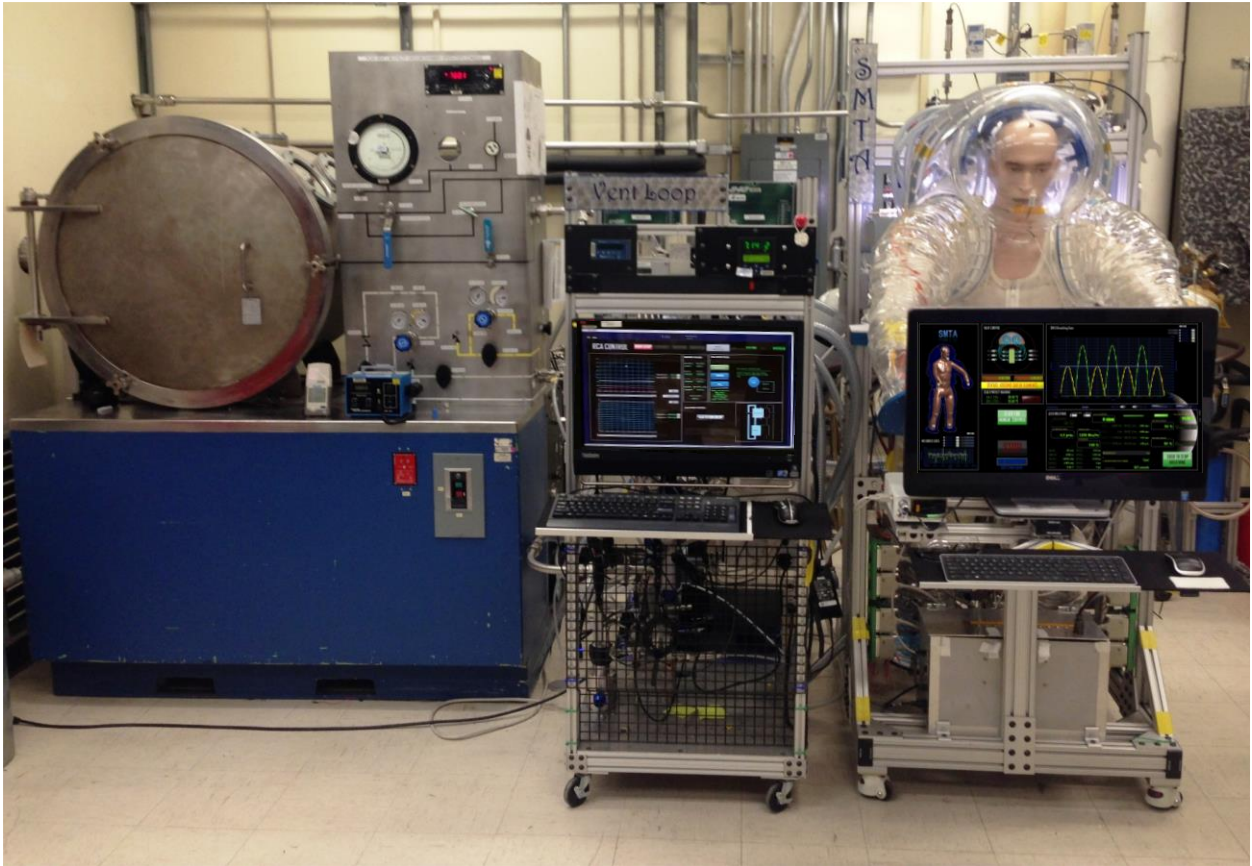


Figure 9. Vacuum Chamber (left), Ventilation Test Loop (middle) and SMTA (right).

Figure 10 shows the simplified layout of the APLSS schematic design as implemented in the PLSS 2.0. This design includes the ventilation loop (highlighted in red dashes), the oxygen supply loop (excluded in the test rig because the laboratory is not rated for oxygen), the SMTA, and the feed air system for breathing. The PLSS test facility is not rated for O₂ and uses N₂ instead of O₂ as the test gas. Metabolic O₂ usage in the SMTA is accomplished by “exhaling” less gas than was “inhaled” by the appropriate amount similar to the actual human breathing function. The function is accomplished with a medical grade compressor.

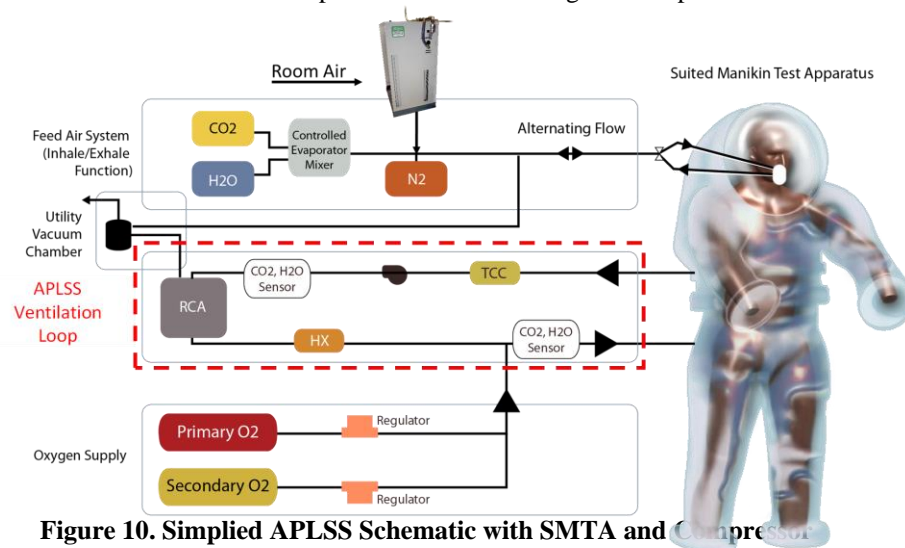


Figure 10. Simplified APLSS Schematic with SMTA and Compressor

A. Ventilation Test Loop

The Ventilation Test Loop design simulates portions of the APLSS ventilation loop as shown in Figure 10. The Ventilation Test Loop was designed to interface with the SMTA and contains the required instrumentation to evaluate the flow rates, humidity, and CO₂ concentrations in the APLSS ventilation loop. The Ventilation Test Loop maintains the desired ventilation loop flow rate using a commercial off-the-shelf (COTS) fan and maintains the system pressure using a COTS regulator. The Ventilation Test Loop also contains a flow meter, CO₂ sensors, and humidity sensors at the inlet and outlet of the RCA to evaluate CO₂ and humidity removal performance. The Ventilation Test Loop interfaces with facility vacuum resources that are used to remove CO₂ and humidity from the desorbing RCA bed. The Ventilation Test Loop combined with the SMTA interfaces to facility N₂ that supplies the test loop with dry N₂ and provides any ullage lost during the RCA valve cycling operation. This replicates the advanced suit pressure regulation function that provides make-up O₂ to replace any ventilation gas losses in the suit or APLSS. The Ventilation Test Loop is shown in Figure 11.

The APLSS ventilation loop contains the following key components:

RCA: The APLSS uses the RCA to remove CO₂ and excess humidity. This technology is regenerable throughout the duration of the EVA and does not need the routine maintenance at the end of each EVA that was required by the Apollo and Shuttle/ISS EMU CO₂ removal units.² The Ventilation Test Loop is configured with the RCA 1.0 prototype.

Fan: The volume of this effective high-speed fan was minimized to help keep the APLSS volume within limits. The fan currently has the capacity to provide 6 actual acfm to the helmet to provide for sufficient CO₂ washout. If the helmet ventilation design becomes more efficient at washing out CO₂, the ventilation rate requirement could be reduced, resulting in fan power reduction. The fan configured in the Ventilation Test Loop is a commercial-off-the-shelf-fan.

Heat Exchanger: The APLSS ventilation loop includes a small but effective heat exchanger that brings the ventilation gas temperature to within 5°F of the thermal control water loop. Meeting pressure drop requirements is one of the drivers of the heat exchanger sizing. If the ventilation flow rate requirement was reduced due to CO₂ washout efficiency improvements in the helmet, the heat exchanger may be able to be reduced further. The Ventilation Test Loop does not contain a heat exchanger since the loop does not have thermal control as a function.

Trace Contaminant Control (TCC): The TCC unit is placed inside the hatch (pressurized volume) of the space suit to allow for convenient periodic change-out of this filter once it becomes saturated. The TCC design may also be able to be reduced in size if the ventilation flow rate requirement was reduced due to CO₂ washout efficiency improvements in the helmet. The TCC function is not currently simulated within the Ventilation Test Loop.



Figure 11. Ventilation Test Loop (side and front views).

B. Suited Manikin Test Apparatus

The SMTA as shown in Figure 12 was developed to augment testing of the APLSS ventilation loop by simulating the ventilation parameters associated with a suited crew member. The SMTA includes a transparent urethane suit based on the geometry of the Mark III space suit with a COTS manikin inside that is augmented with breathing capability to emulate the human in the space suit. Correlation of space suit ventilation math models becomes challenging because of human variability and movement. The SMTA can now provide a stable, easily modeled alternative to human CO₂ washout testing. The performance of the RCA in the APLSS ventilation loop can be more adequately evaluated using the SMTA. This uniquely designed SMTA with its breathing capability provides NASA the ability to evaluate off-nominal CO₂ washout conditions that would otherwise be unsafe, difficult, and very expensive for human testing due to test subject fatigue. This innovative and unique SMTA is NASA's only breathing manikin test capability. Its main objective is to validate the advanced CO₂ removal hardware performance and CO₂ washout.¹¹

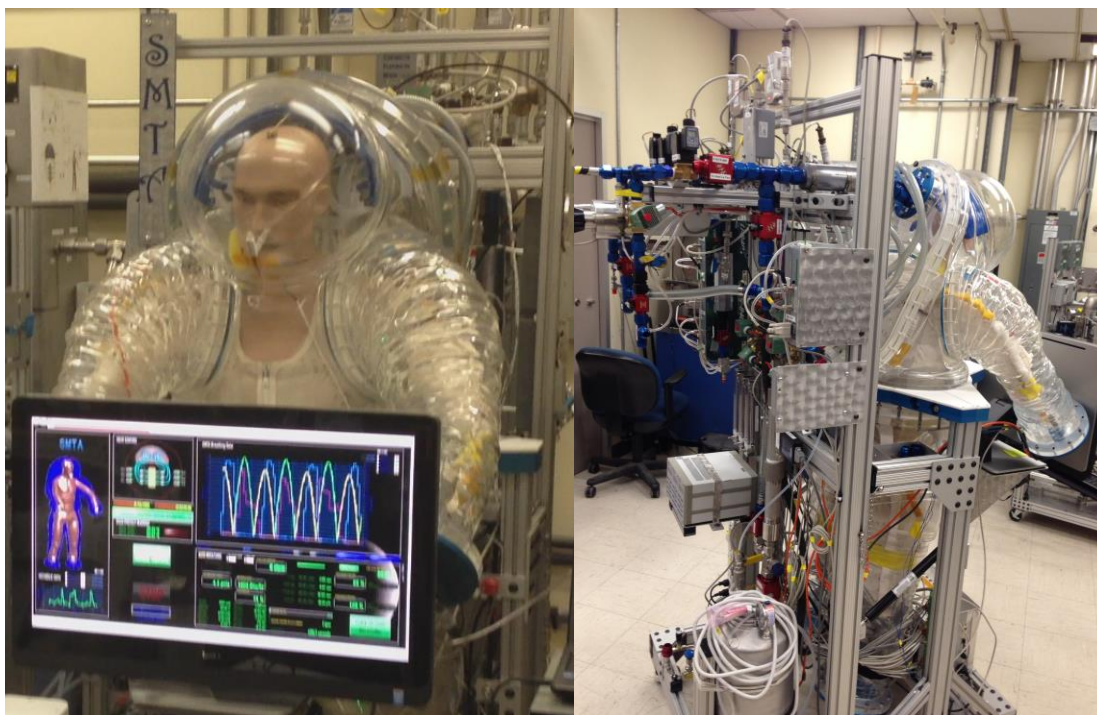


Figure 13. SMTA (front and side)

The SMTA has the ability to simulate various metabolic conditions. Total gas pressure within the SMTA can also be varied from 4 psia to 19 psia to simulate a wide range of suit pressures experienced during flight and test scenarios. The SMTA operates with a human breathing profile. However, the SMTA is not O₂ rated, and N₂ or room air is used to simulate O₂.

The SMTA maintains the desired simulated metabolic rate by injecting the proper amounts of CO₂ and water vapor (H₂O) into the breathing stream. A flow controller supplies the proper amount of facility CO₂ to a controlled evaporation mixer (CEM) unit to simulate the desired metabolic load. The CEM controls the amount of liquid water flowing from the SMTA water tank to be mixed with the CO₂ and heats this mixture to vaporize the proper amount of metabolic H₂O injected in the breathing gas stream.

A total of nine CO₂ sensors are used within the SMTA test stand. Two CO₂ sensors are installed in the inhale and exhale lines to monitor and record CO₂ levels. A Portable Unit for Metabolic Analysis (PUMA) CO₂ sensor¹² is installed within the mouth of the manikin to monitor and record the inhaled and exhaled CO₂ concentration levels. Five additional CO₂ sensors are installed internal to the SMTA suit volume and external to the manikin to monitor and record CO₂ levels at various locations within the suit. Lastly, a CO₂ sensor is installed on the flow stream exiting the suit that returns to the Ventilation Test Loop.

The vacuum system connected to the test loop draws the system pressure down to the desired operating pressure for sub-ambient testing. Also, a humidity sensor is installed in the inhale-exhale line just outside of the suit volume of the SMTA to measure the humidity levels during the inhale and the exhale breathing cycles.

C. Feed Air System

The breathing exhale system of the SMTA mixes the CO₂ and H₂O mixture exiting the CEM with compressed air to create a characteristic breathing profile, ported orally to the manikin's mouth through the back of the manikin's neck. The compressed air is supplied by a medical-grade air compressor. The simulated exhale breath of the manikin is controlled by a mass flow controller, a mass flow meter, a back pressure regulator, and a solenoid valve. These components work together to supply the air stream containing CO₂ and H₂O to the manikin. A real time algorithm adjusts the exhale flow rate to properly simulate metabolic O₂ consumed. The simulated inhale breath is controlled by one mass flow meter and two solenoid valves ported to the vacuum system. Each set of mass flow controllers and solenoid valves alternate to simulate a breathing test subject.

V. 2016 Carbon Dioxide Washout Testing

(this section will be added with final as test points are just now being performed)

VI. Summary and Future Plans

(this section to be updated in final with conclusions from test results)

Initial CO₂ washout testing has been performed with the SMTA and the Ventilation Test Loop, demonstrating the capabilities and early benefits that these units can provide. Human testing can be supplemented with SMTA testing to reduce total costs and to provide a stable repeatable configuration to provide a better basis for CFD model correlation efforts and benefits for the testing and evaluation of ventilation loop sensors and components. The combination of testing and analysis should help understand differences that have been experienced with prior human testing and CFD modeling predictions. The SMTA and the Ventilation Test Loop together are envisioned to provide a platform for gaining knowledge of CO₂ washout characteristics and help resolve these differences.

The potential benefits from optimizing CO₂ washout performance include:

- Reduced APLSS/space suit ventilation flow rate requirements that could reduce power and fan performance requirements.
- Reduced efficiency requirements for the APLSS CO₂ removal unit (RCA).
- Reduced emergency purge flow rate requirements that would allow for smaller quantities of emergency oxygen to be stored within the APLSS.
- More robust helmet/ducting designs that are less sensitive to head position, head size, hair/communications hardware configurations.
- More predictable CO₂ washout performance that reduces the risk of elevated CO₂ levels and their effects on human performance.

It is recommended that these investigations continue in order to quantify the risks associated with variations in crew member sizes and positions and to optimize ducting into and out of the helmet/space suit. These investigations should include human testing, SMTA testing and CFD simulations of corresponding conditions and configurations. A few configurations have been investigated, but many potential configurations exist that may provide better CO₂ washout performance for the AEMU and future space suits. Parameters that should continue to be investigated are:

- Breathing patterns (flow rates and frequencies)
- Mouth/nose flow split
- Variations in head sizes and shapes including hair and head gear impacts
- Head orientation within the helmet (height in the suit/turned head variations)
- Communications hardware configurations within the helmet
- Helmet ducting inlet and outlet locations
- Helmet ventilation flow rate variations
- Helmet inlet CO₂ levels
- Helmet design (shape)
- Metabolic rate variations

The CO₂ washout test equipment and hardware is not currently configured to test the cold case environments that would exacerbate fogging. Prior investigations have determined that there are alternative strategies to reduce fogging if helmet gas flow characteristics cannot fully resolve fogging issues.¹³ Aspects of fogging were not addressed in this paper but should be a future consideration.

Additionally, future uses of the SMTA include CO₂ and purge efficiency evaluations of suit geometries other than the current Mark III suit, and CO₂ buildup of mask systems that are not dependent on the suit geometries. Evaluations of masks that fit over the head can be accomplished easily with the SMTA because the entire unit can function when the manikin head is tilted back away from the suit volume. Potential mask evaluations could include masks used for aviation, firefighting, and underground mining.

In summary, the SMTA and Ventilation Test Loop are valuable resources for JSC. Evaluations being conducted show that CO₂ washout may be sensitive to helmet and head configurations. Plans are in place to perform further testing with humans and with the SMTA to provide insight into CO₂ washout variables and to provide guidance for the AEMU. These efforts are targeted to provide robust, safe, and efficient space suit designs.

Acknowledgments

The authors of this paper would like to acknowledge the entire Advanced Space Suit team for their concerted efforts toward the design, buildup, and testing of the Advanced Space Suit subsystems and their components thus far. It has been more than 40 years since a complete space suit of this magnitude has been designed, built, and tested. Also, the authors would like to thank the programs that contributed to the funding and successes achieved thus far. Finally, the authors would like to thank the leadership of the Crew and Thermal System Division for the dedicated laboratories to accomplish the testing.

References

- ¹Papale, W., Paul, H., Thomas, G., "Development of Pressure Swing Adsorption Technology for Spacesuit Carbon Dioxide and Humidity Removal," *36th International Conference on Environmental Systems*, SAE, 2006-01-2203, Norfolk, VA, July 17-20 2006.
- ²Papale, W., Chullen, C., Campbell, C., Coin, J., Wichowski, R., "Rapid Cycle Amine (RCA 2.0) System Development," *43rd International Conference on Environmental Systems*, AIAA-2013-3309, Vail, CO, July 14-18, 2013.
- ³Papale, W., Chullen, C., Campbell, C., Conger, B., McMillin, S., "Continued Development of the Rapid Cycle Amine System for Advanced Extravehicular Activity Systems," *44th International Conference on Environmental Systems*, ICES-2014-196, Tucson, AZ, July 13-17, 2014.
- ⁴Chullen, C., Campbell, C., Papale, W., Hawes, K., and Wichowski, R., "Rapid Cycle Amine 3.0 System Development," *45th International Conference on Environmental Systems*, ICES-2015-313, Bellevue, WA, July 12-16, 2015.
- ⁵Law J., Watkins, S., and Alexander, D., "In-Flight Carbon Dioxide Exposures and Related Symptoms: Association, Susceptibility, and Operational Implications," NASA/ TP-2010-216126, June 2010.
- ⁶Mitchell, K., Korona, A., and Norcross, J., "Advanced Space Suit CO₂ Washout Test Report," NASA Johnson Space Center, CTSD-ADV-1032, Houston, TX, December 12, 2012.
- ⁷Korona, A., and Norcross, J., "Z-1 Suit CO₂ Washout Test Report," NASA Johnson Space Center, CTSD-ADV-1024, Houston, TX, November 23, 2012.
- ⁸Korona, A., and Norcross, J., Conger, B., Navarro, M., "Carbon Dioxide Washout Testing Using Various Inlet Vent Configurations in the Mark-III Space Suit," *44th International Conference on Environmental Systems*, ICES-2014-55, Tucson, AZ, July 13-17, 2014.
- ⁹Norcross, J., and Bekdash, O., "CO₂ Washout Sampling Method Recommendation for the Z-2 CO₂ Washout Study," Biomedical Research and Environmental Sciences/SK, NASA Johnson Space Center, Houston, TX, January, 2016 (unpublished).
- ¹⁰Chullen, C., Navarro, M., Conger, B., Korona, A., McMillin, S., Norcross, J., Swickrath, M., "Maintaining Adequate Carbon Dioxide Washout for an Advanced Extravehicular Mobility Unit", *43rd International Conference on Environmental Systems*, AIAA-2013-3341, Vail, CO, July 14-18, 2013.
- ¹¹McMillin, S., "Suited Manikin Test Apparatus (SMTA) Test Plan," NASA CTSD-ADV-1039, Houston, TX, Jan. 2013.
- ¹²Dietrich, D., Juergens, J., Lewis, M., Lichter, M., Easton, J., McCleary, F., "A Portable Unit to Measure Metabolic Rate during Shirtsleeve and Suited EVA Tests," *38th International Conference on Environmental Systems*, 2008-01-2110, San Francisco, CA, 29-30 June and 01-02 July 2008.
- ¹³Navarro, M., Conger, B., and Campbell, C., "Exploration Extravehicular Activity Purge Flow Assessment," *41st International Conference on Environmental Systems*, AIAA 2011-5220, Portland, OR, 17-21 July 2011.